ICRU Report 95:
Operational Quantities for External Radiation Exposure
Impact on Environmental Measurements

ICRU Symposium 2023

Revitalization of Fukushima and Radiation Measurement

Thomas Otto, ICRU and CERN

Contents

- Protection and Operational quantities
- New operational quantities in ICRU 95
- Changes in conversion coefficients for ambient dosimetry
- Consequences:
  - Dosimetry in realistic radiation fields
  - Environmental dosimeter response
- Summary

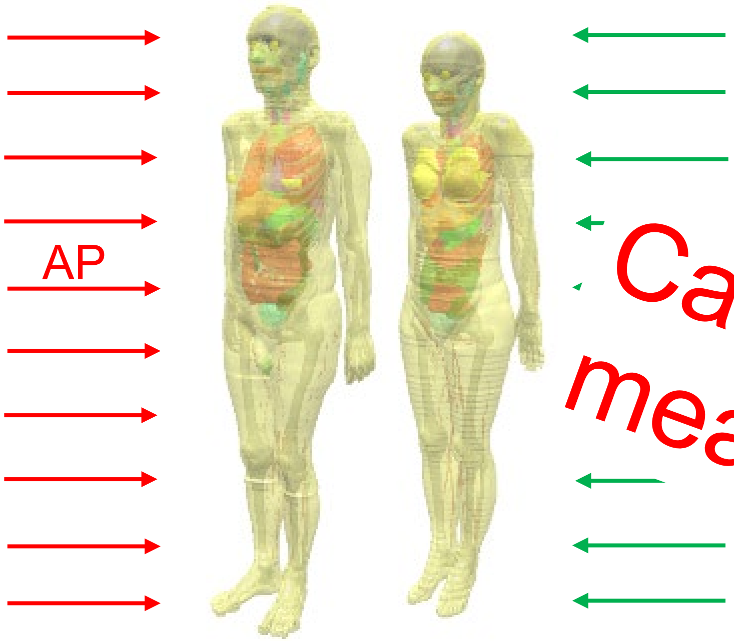
Protection Quantities

- ICRP defines Protection Quantities, to compare radiation detriment with limits and to enable optimization.
- Unifying concept to estimate radiation detriment from
  - External exposure
  - Internal exposure
- To organs (tissues) and whole body:
  - $D_{R,T} = \frac{1}{m_T} \int D_R \cdot dm$ Mean Organ Dose
  - $E = \sum_T w_T \sum_R w_R D_{R,T}$ Effective Dose

- Dose limits and constraints expressed in protection quantities

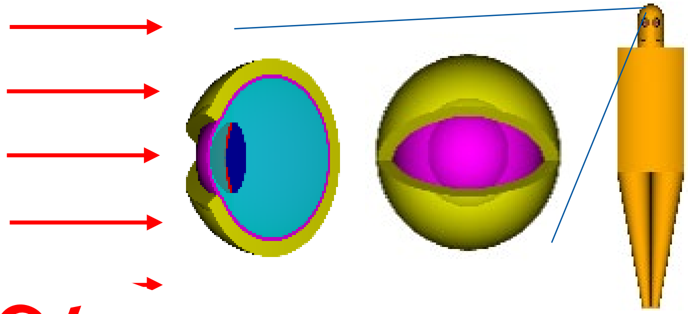
Calculation of Protection Quantities

- Whole Body: E



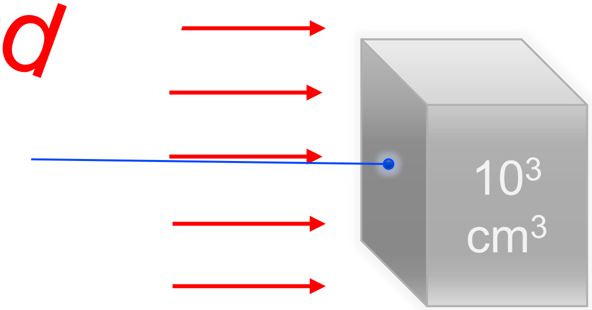
and other directions

- Eye lens: $H_{\mathrm{T\ lens}}$



Cannot be measured

- skin: $H_{\mathrm{T\ skin}}$



Phantoms: ICRP Report 110
Conversion Coefficients: ICRP Report 116

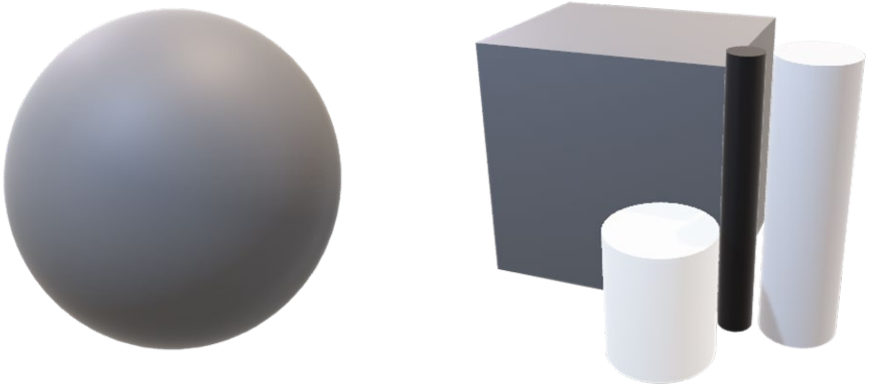
Operational Quantities

- Defined in a single point – in principle measurable
- Defined as (ICRU 39)

$$\boxed{H(d) = D(d) * Q(L)}$$

- Dose equivalent = absorbed dose in depth d * quality factor

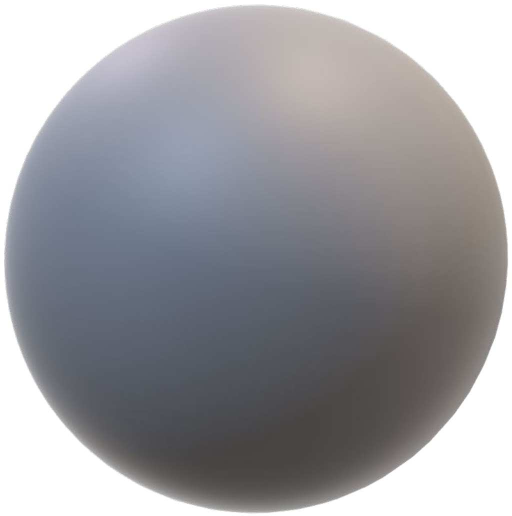
Calculation of conversion coefficients with phantoms in the shape of simple geometrical bodies



Calculation of conversion coefficients for present Operational Quantities

Area Monitoring

ICRU sphere



Personal Monitoring

slab and cylinder phantoms

(surrogates for trunk, head and extremities)

Phantoms are made from ICRU-4-component tissue surrogate (numerical)

Present Relation of Quantities

Physical Quantities
Φ, K_a, D

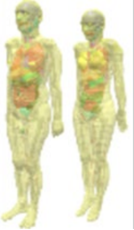
Definition

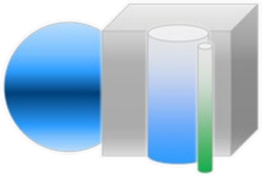
Definition

Protection Quantity
Effective dose E

Operational Quantities
Ambient dose equivalent $H^*(10)$
Personal dose equivalent $H_p(10)$

Calculation:
anthropomorphic
phantoms, w_R, w_T





Calculation:
geometric
phantoms, Q(L)

$$E = \int dE_p \, \Phi_{E_p} h_E(E_p, \text{inc}^*)$$

$$\neq$$

$$H_p(d,\Omega) = \iint dE_p d\boldsymbol{\Omega} \, \Phi_{E_p} h_p\left(d, E_p, \boldsymbol{\Omega}\right)$$

$$H^*(d,\Omega) = \iint dE_p d\boldsymbol{\Omega} \, \Phi_{E_p} h^*\left(d, E_p, \boldsymbol{\Omega}\right)$$

* incident directions: AP, PA, LLAT, RLAT, ROT, ISO

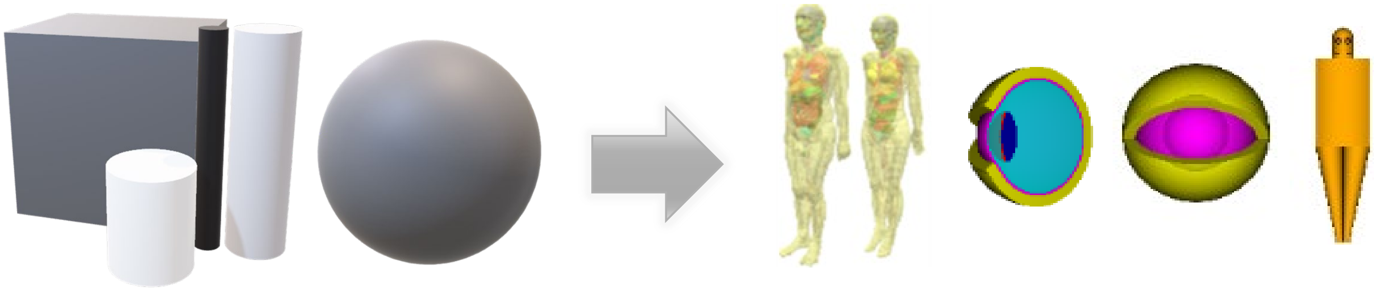
For photons in kerma approximation

Measurement
Instrument response $R\ (E,\Omega)$

New Operational Quantities in ICRU 95

$$\boxed{H = h_\varphi \cdot \Phi_{E_\mathrm{p}}}$$

- Use of anthropomorphic phantoms and w_T, w_R



- Better approximation of E and H_T *by definition*
- Definition of quantities to limit tissue effects (local dose to skin and to eye lens) as **absorbed dose**
- More radiation types, e.g. positrons, protons, pions… & wider energy range

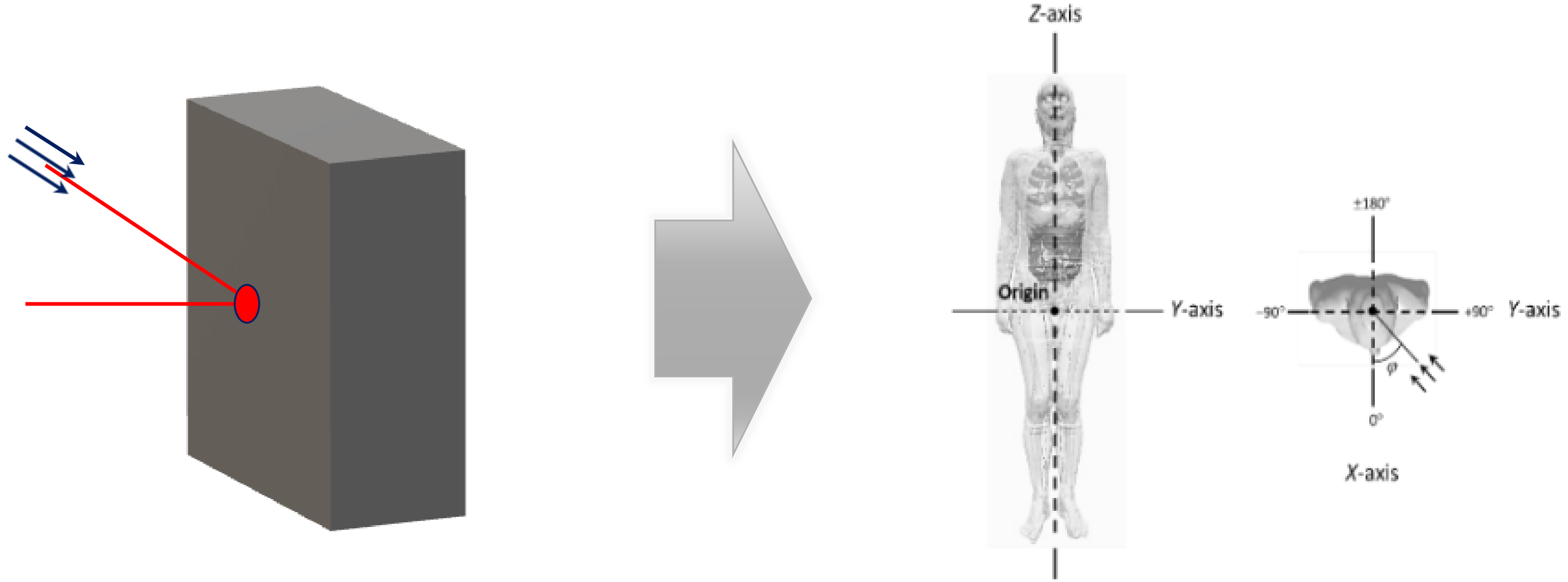
Whole-body personal dosimetry

Personal Dose Equivalent $H_p(10)$

- $H_p(10) = D(10) * Q(L)$
- 10 mm under the center of the ICRU-4-component tissue slab
- Expanded Radiation Field

Personal Dose H_p:

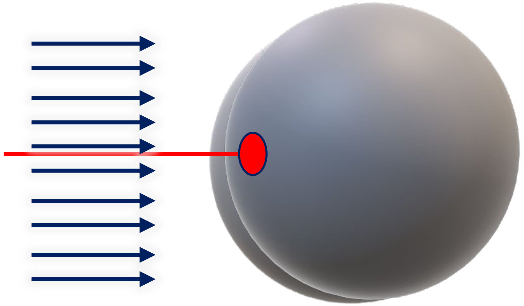
- Calculated as weighted sum (w_R,w_T) of organ doses in anthropomorph phantom
- Plane-parallel radiation field from defined direction



Ambient Dosimetry

Ambient Dose Equivalent *H**(10)

- $H^*(10) = D(10) * Q(L)$
- Absorbed dose in 10 mm depth in the ICRU sphere
- Expanded and aligned field (all radiation field components assembled under 0°)

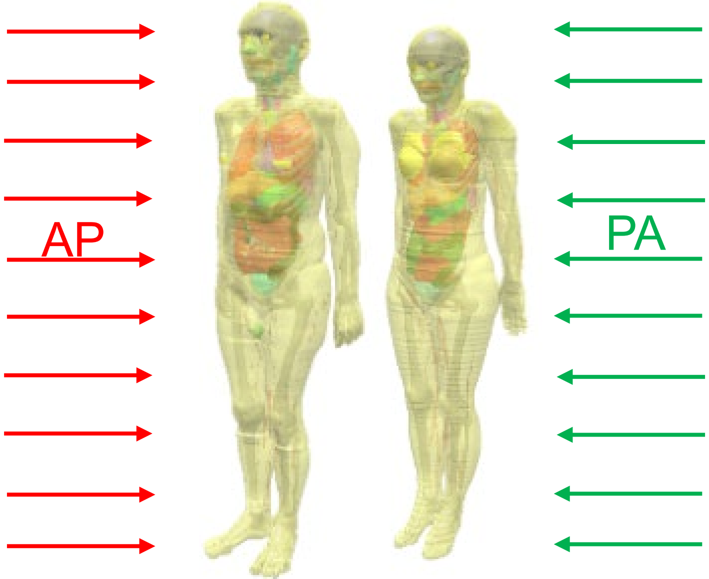


Ambient Dose *H**

Maximum of Effective Dose over the directional coefficients listed in ICRP Report 116

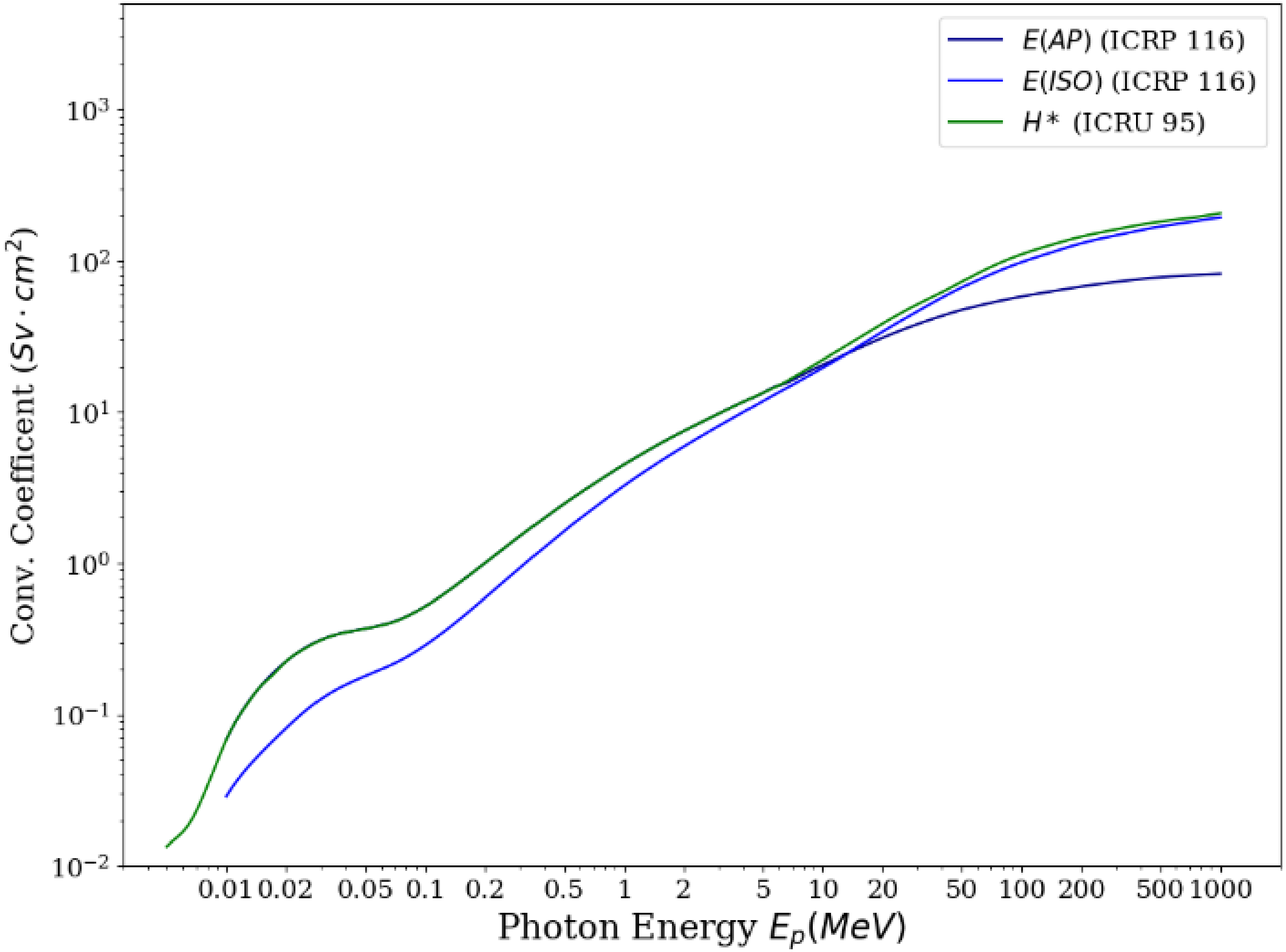
$$H^* = h_{E_{\max}} \cdot \Phi$$

$$h_{E_{\max}}(E_p) = E_{\max}(E_p) / \Phi(E_p)$$

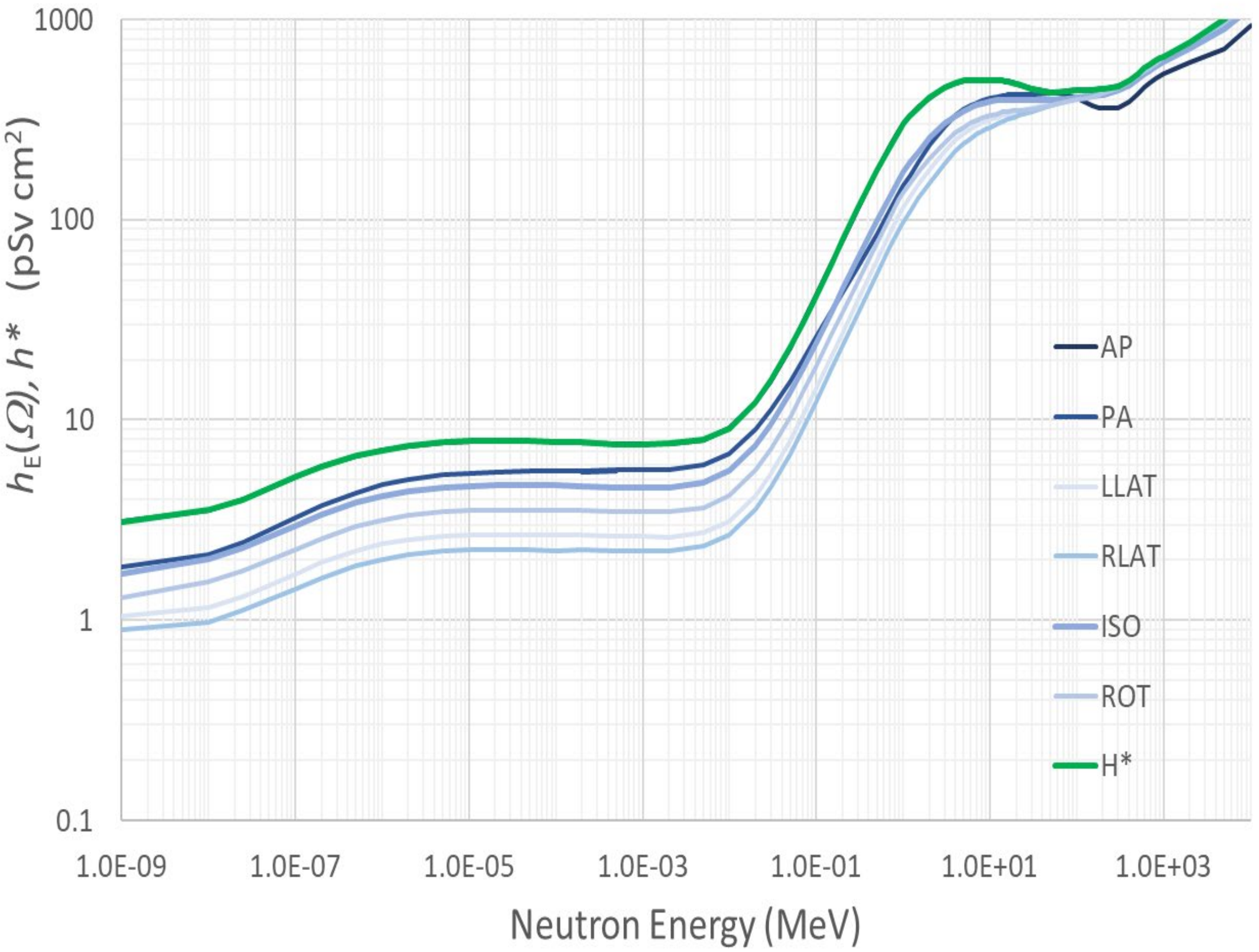


and 4 other directions

E, *H**(10) and *H** for Photons



E, *H**(10) and *H** for Neutrons



ICRU Report 95 Relation of Quantities

Physical Quantities
Φ, K_a, D

Definition

Definition

Protection Quantity
Effective dose E

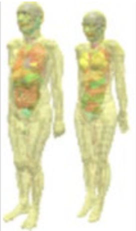
Calculation:
anthropomorphic phantoms, w_R, w_T

$$E = \int dE_p \, \Phi_{E_p} h_E(E_p, \mathrm{inc}^*)$$

* incident directions: AP, PA, LLAT, RLAT, ROT, ISO

$$\triangleq$$

Operational Quantities
Ambient dose H^*
Personal dose H_p



Calculation:
anthropomorphic phantoms, w_R, w_T

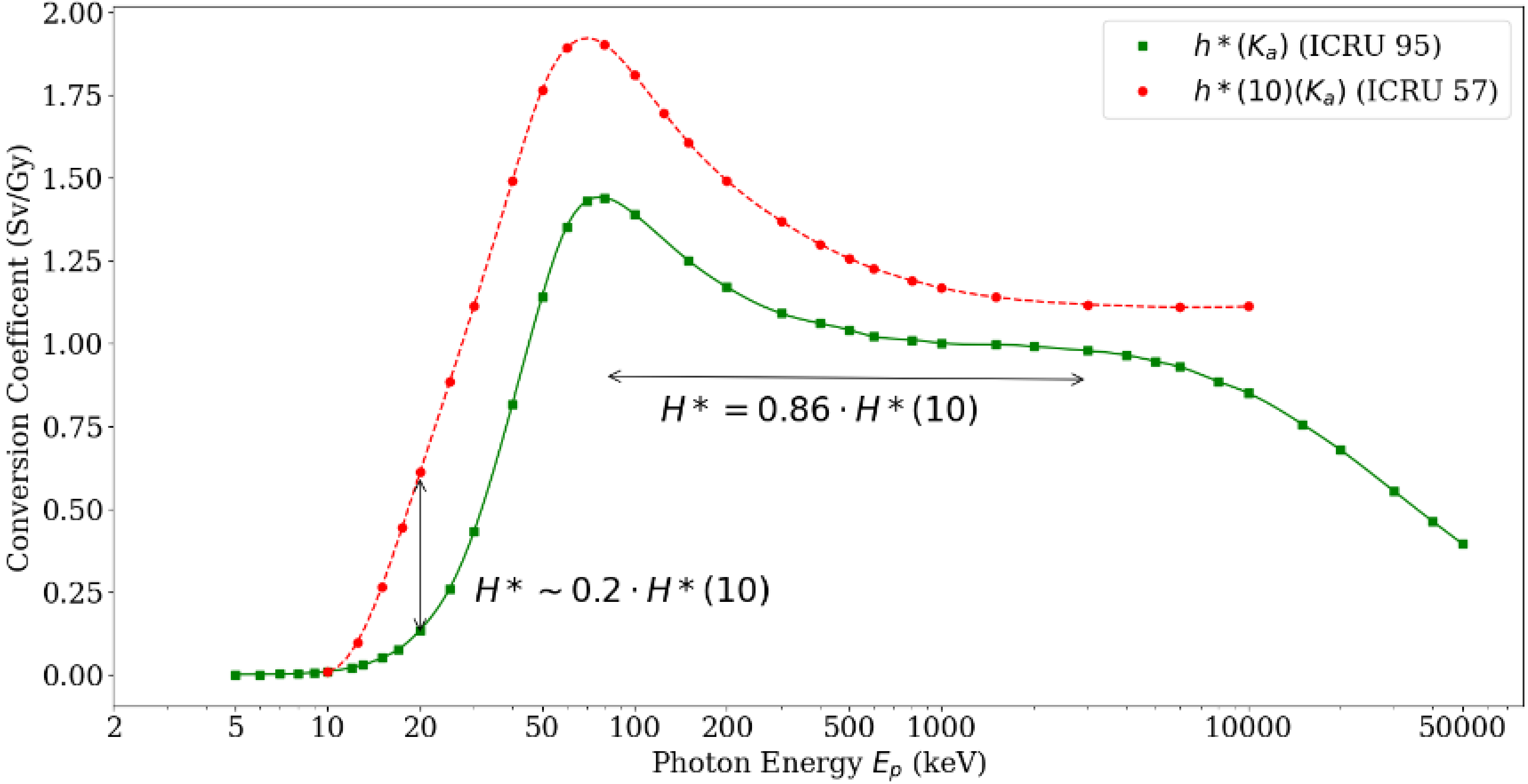
$$H^* = \int dE_p \, \Phi_{E_p} \cdot h_{E_{max}}(E_p)$$

$$H_p = \iint d\Omega \, dE_p \, \Phi_{E_p} \cdot h_p(E_p, \boldsymbol{a})$$

Measurement
Instrument response $R\ (E,\Omega)$

Ambient dose – Photons

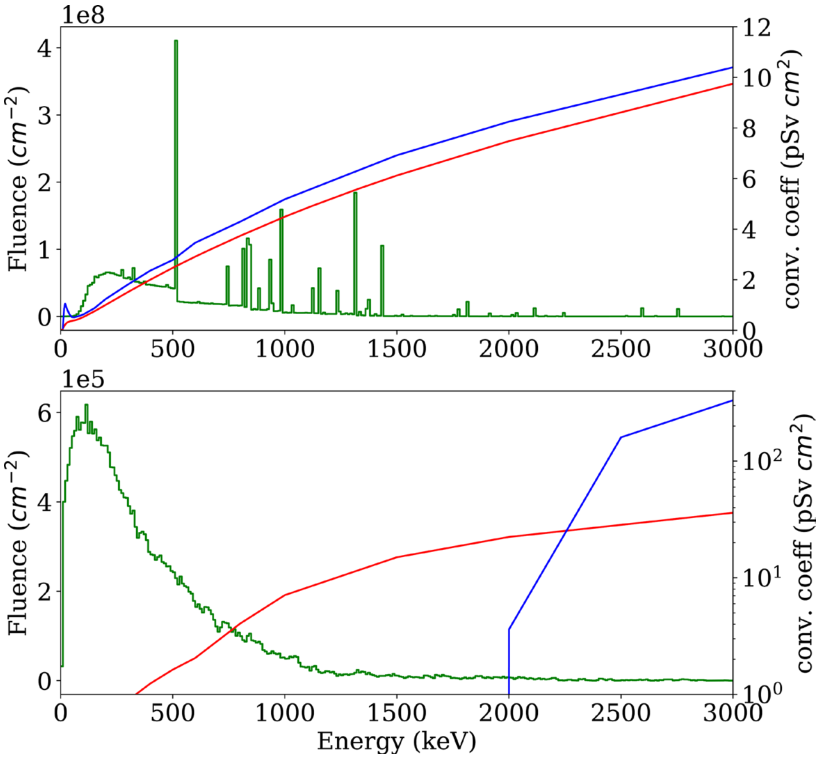
Conversion coefficients from **kerma K_a** to operational quantity



At energies typical for radioisotopes, $H_p = 0.86 * H_p(10)$

At low-energy x-ray (backscatter from patient) $H_p = 0.2 * H_p(10)$

Monte-Carlo Simulation Study: Activation at an Accelerator Workplace



Activation with 3.5 GeV proton beam

Photon and electron spectra (1h decay)

***H**(10) and *H** overlay**

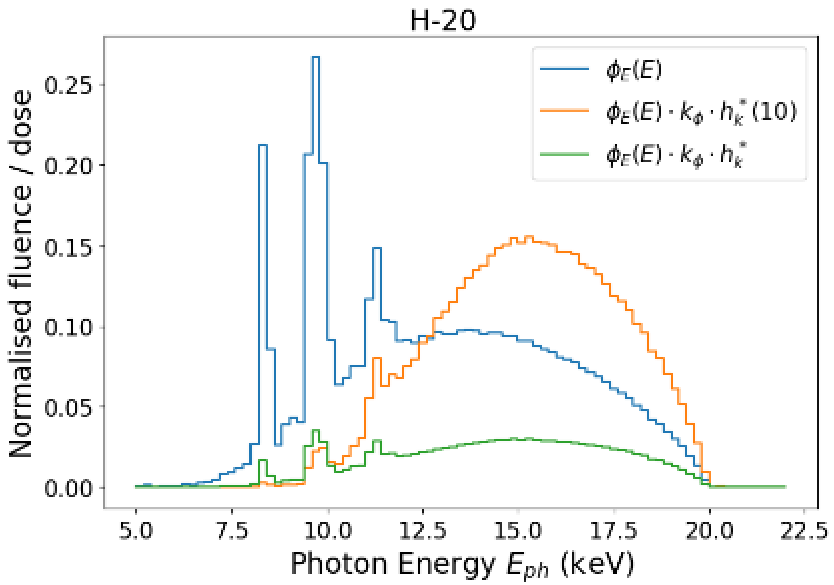
Ratio *H** / *H**(10)

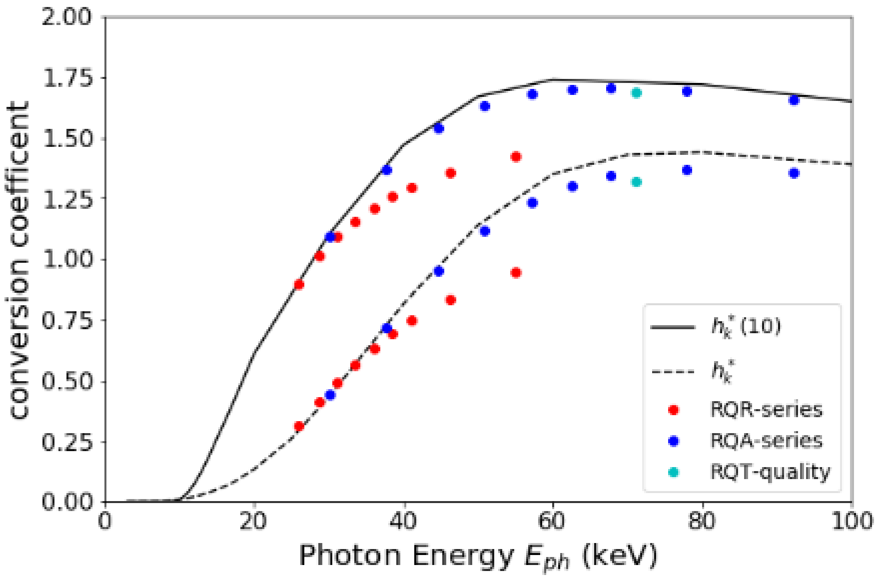
Decay Time	1 hour	1 week	1 year
Photon	0.87	0.86	0.86
Electron	2.9	2.0	2.2
Positron	0.9	1.0	1.0
Total	**0.87**	**0.87**	**0.86**

- Photons dominate
- ***H**** **≈ 0.86** ***H****(10)**
- Typical for radionuclides
- Attention in predominantly beta-fields

Th. Otto & M. Widorski,
Int'l. Particle Accelerator Conference 2021,
10.18429/JACoW-IPAC2021-TUPAB316

Low-energy x-ray spectra





High-dose rate spectrum,
20 kV tube voltage

Fluence spectrum

*H**(10)-weigthed spectrum

*H**-weighted spectrum

Influence on dose of medical personnel during interventional radiology under study

Diagnostic x-ray calibration spectra

Upper curve: *H*(10)*

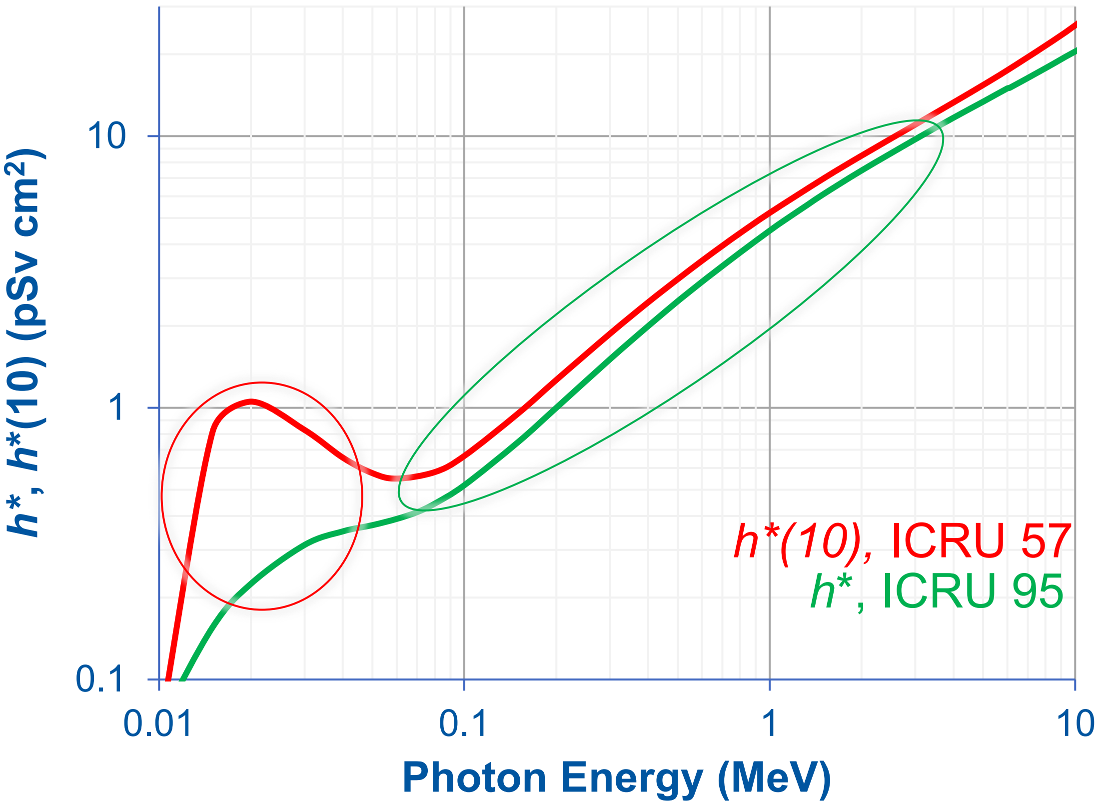
Lower curve: *H**

*H** ≈ *H**(10) in broad spectra

T. Otto, JINST 14 P11011 (2019)
T. Otto, R. Behrens, J. Rad. Prot **139** (2020)

Calibration of photon dosimeters

Conversion coefficients from **fluence ϕ** to operational quantity



The dosimeter can be recalibrated

The energy-dependent response function of the dosimeter must be modified

Response of dosimeters

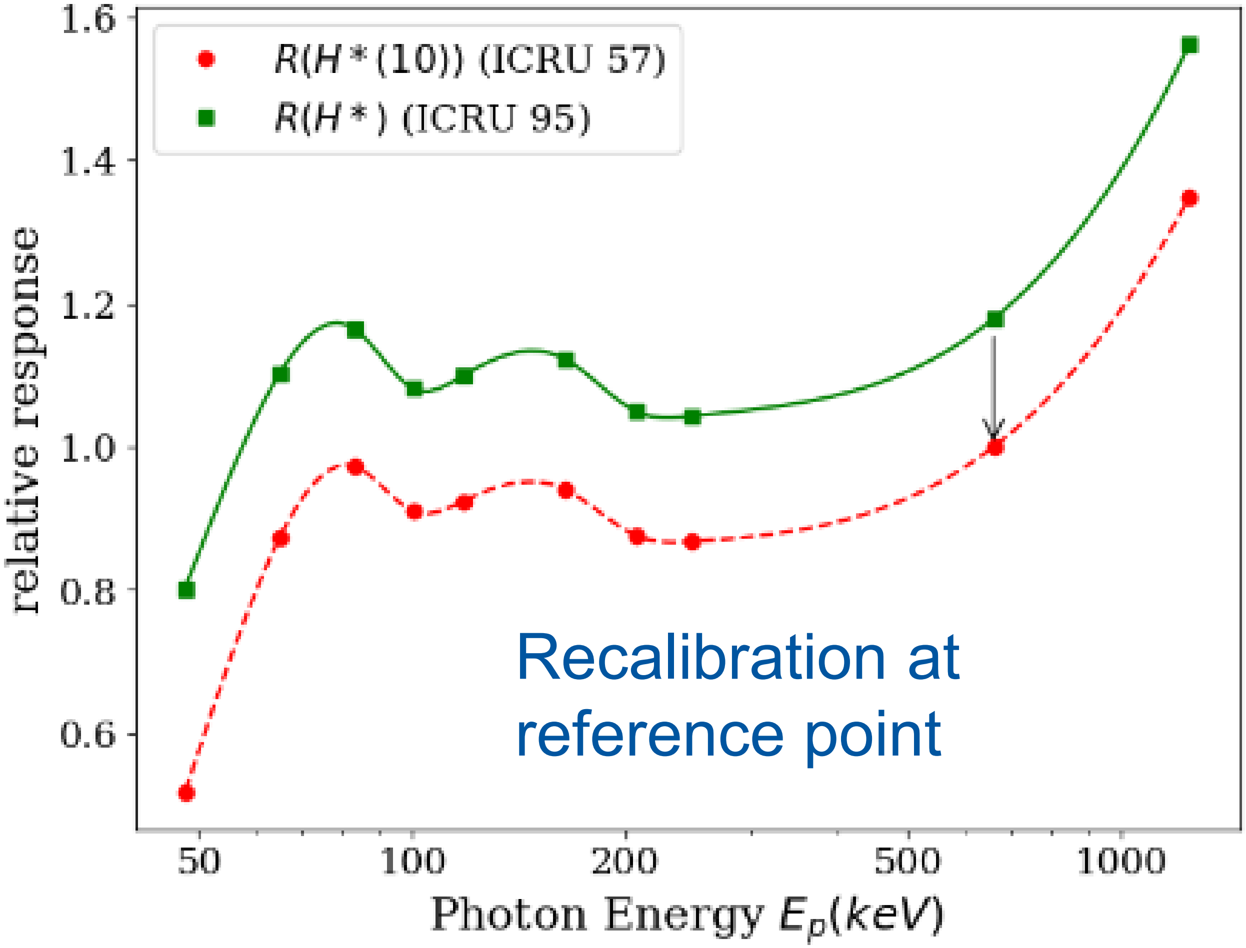
- *Response:* $R = \frac{G}{C}$
  - Dose Indication *G* /Conventional true value *C*
- Change of quantity: $C_{old} \rightarrow C_{new}$
- Dose indication remains the same: $G \rightarrow G$

- Response of dosimeter in the new quantity:

$$R_{\mathrm{new}} = \frac{G}{C_{\mathrm{old}}} \frac{C_{\mathrm{old}}}{C_{\mathrm{new}}} = R_{old} \frac{C_{\mathrm{old}}}{C_{\mathrm{new}}} = R_{old} \frac{h_{\mathrm{old}}}{h_{\mathrm{new}}}$$

Response of Survey instrument

Based on
G-M counter

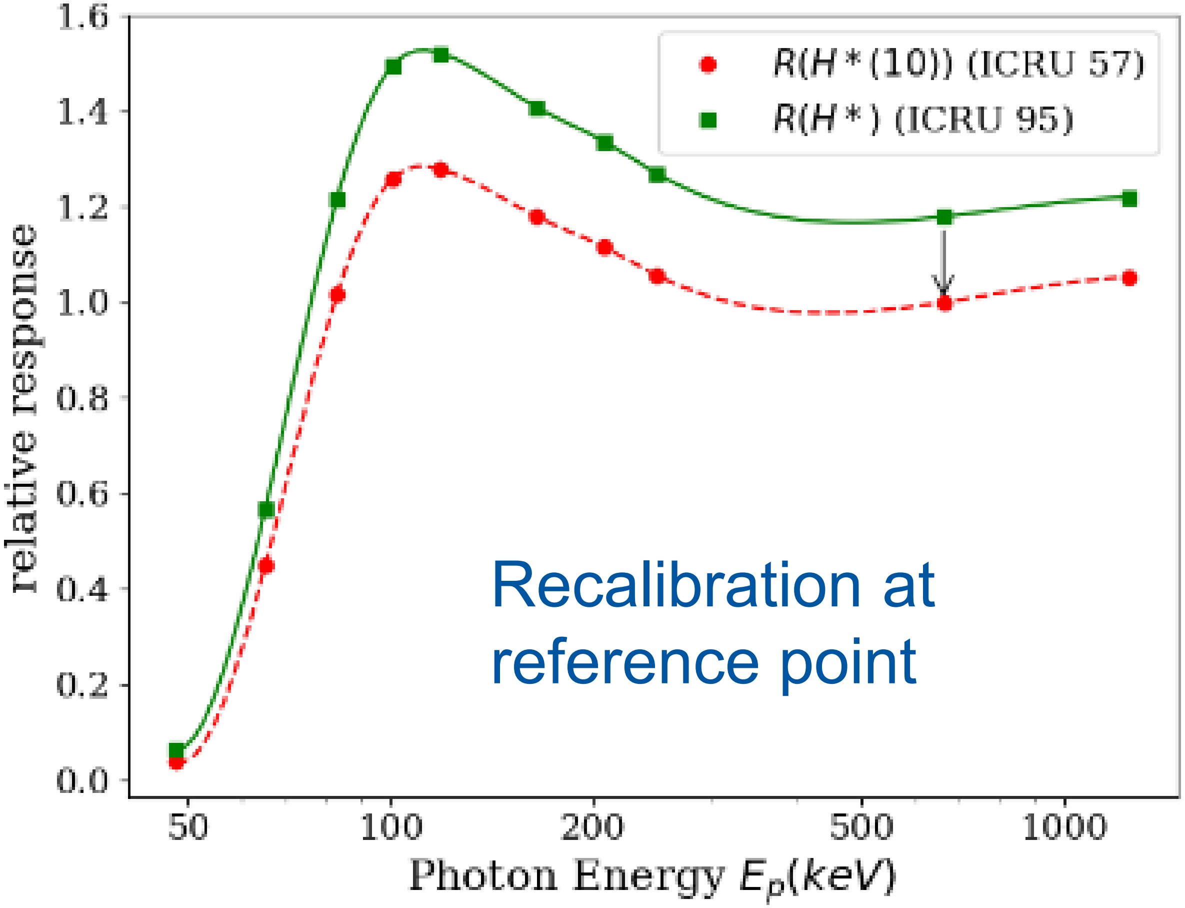


Recalibration at reference point

T. Otto, *JINST* **14** P01010, 2019

Response of HPIC for Photons

Centronics high-pressure ionization chamber

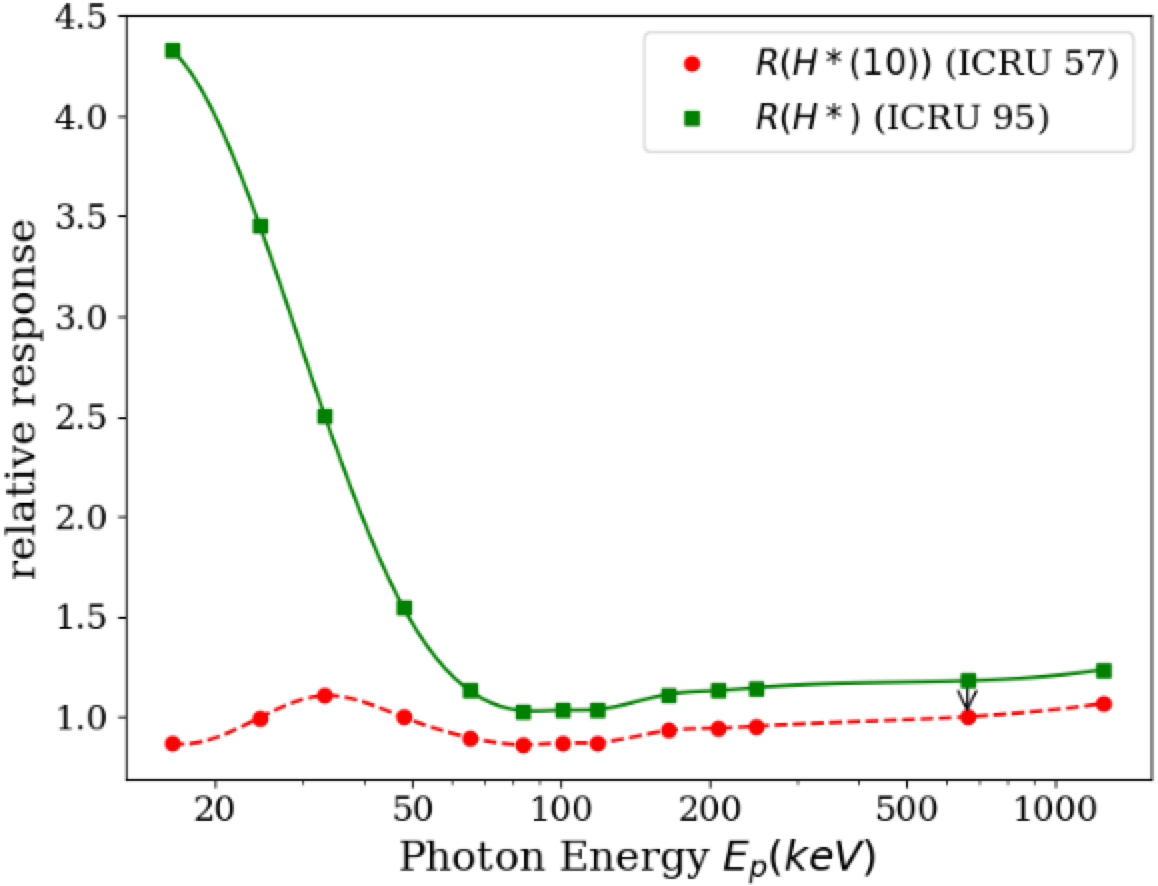


Recalibration at reference point

T. Otto, *JINST* **14** P01010, 2019

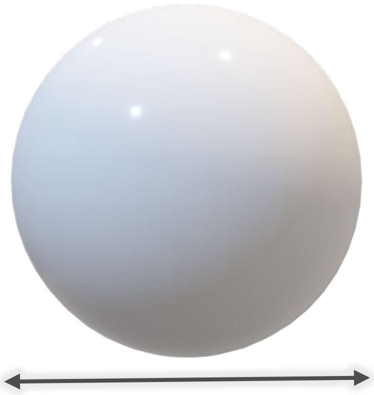
Response of Environmental TLD

“Seibersdorf” cylinder
6 cm Ø x 6 cm, PMMA
1 or 2 Harshaw TLD cards

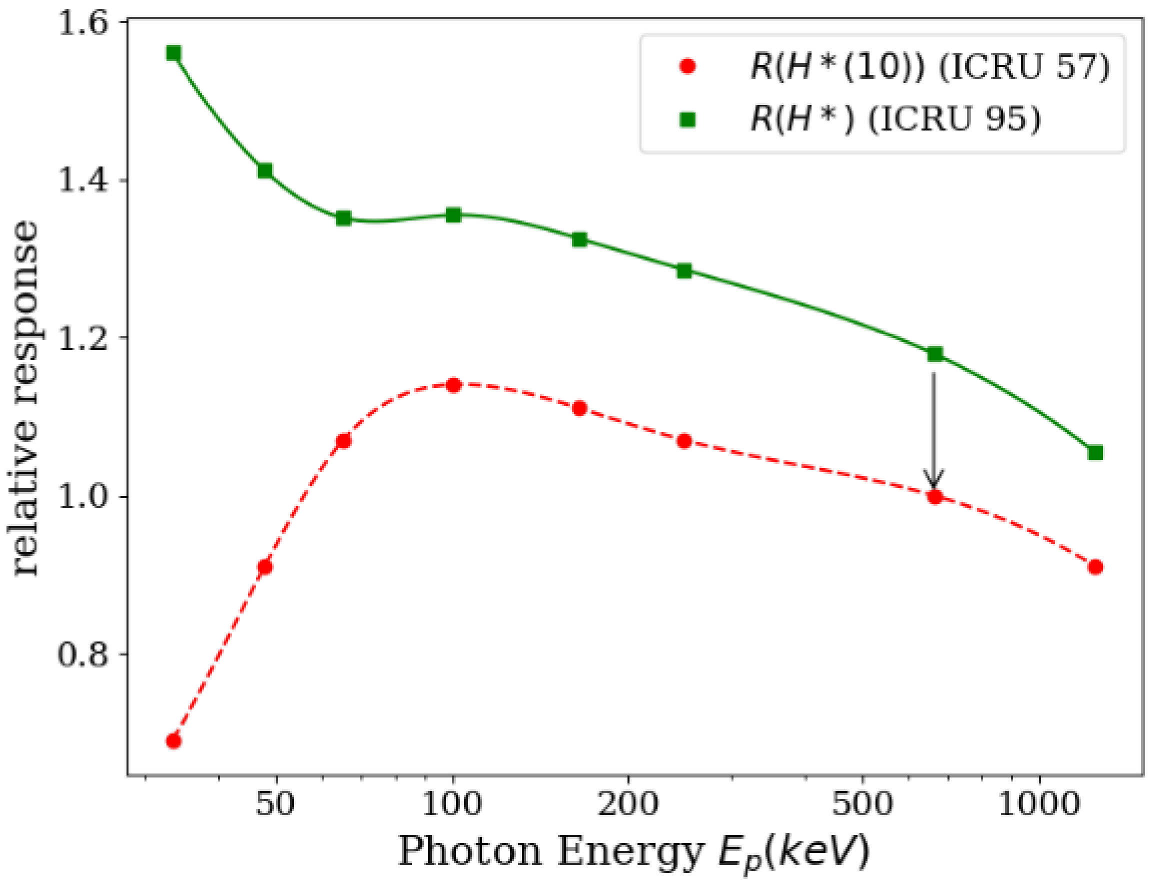


C. Hranitzky and H. Stadtmann, Rad. Meas. **43** (2008) 520 ff.

Response of Environmental TLD



PMMA sphere,
central LiF detector

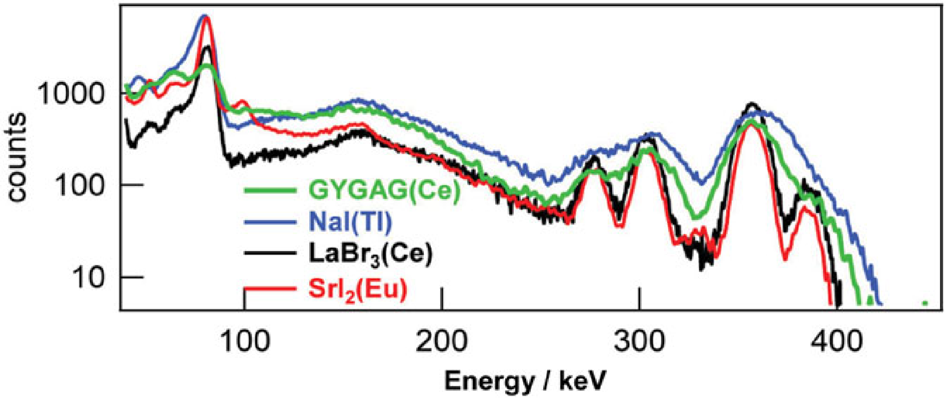


C. A. Carlsson et al., Rad. Prot. Dosim. **67** (1996) 33 ff.

Spectrometer Environmental Monitors

NaI-scintillator-based environmental monitor

(ICRU Report 92)



$$\begin{pmatrix} \% & \cdots & \div \\ \vdots & \ddots & \vdots \\ + & \cdots & \& \end{pmatrix}$$

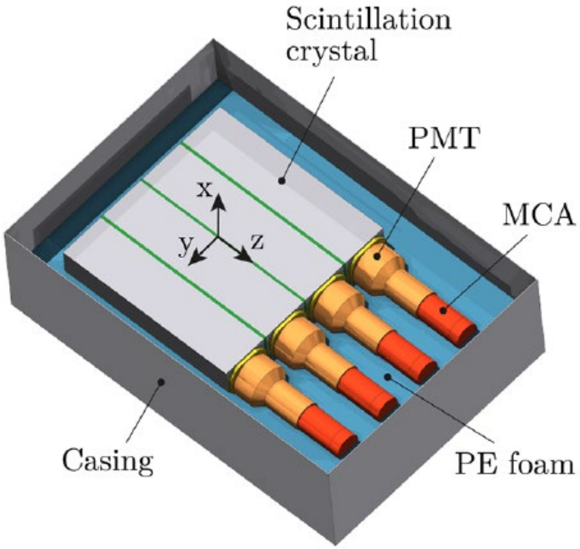
Response Matrix

Φ, K_a, H^*

For example:
Yi et al., Rad. Prot. Dosim. **74** (1994) 273 ff.
Grasty et al., Rad. Prot. Dosim. **94** (2001) 309 ff.
Dombrowski, Rad. Prot. Dosim. **160** (2014) 269 ff.

Aerial Survey Measurements

Flight Path
(ICRU Report 92)

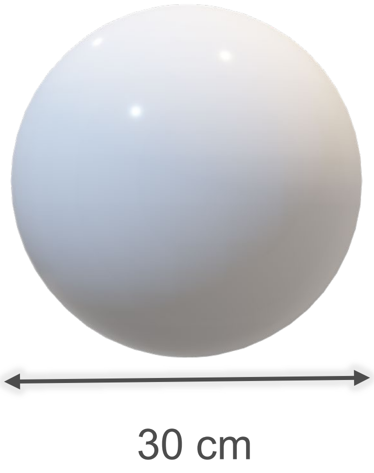


spectrometer-detector
(Breitenmoser et al., Adv. Geosci. **57** (2022) 89 ff.

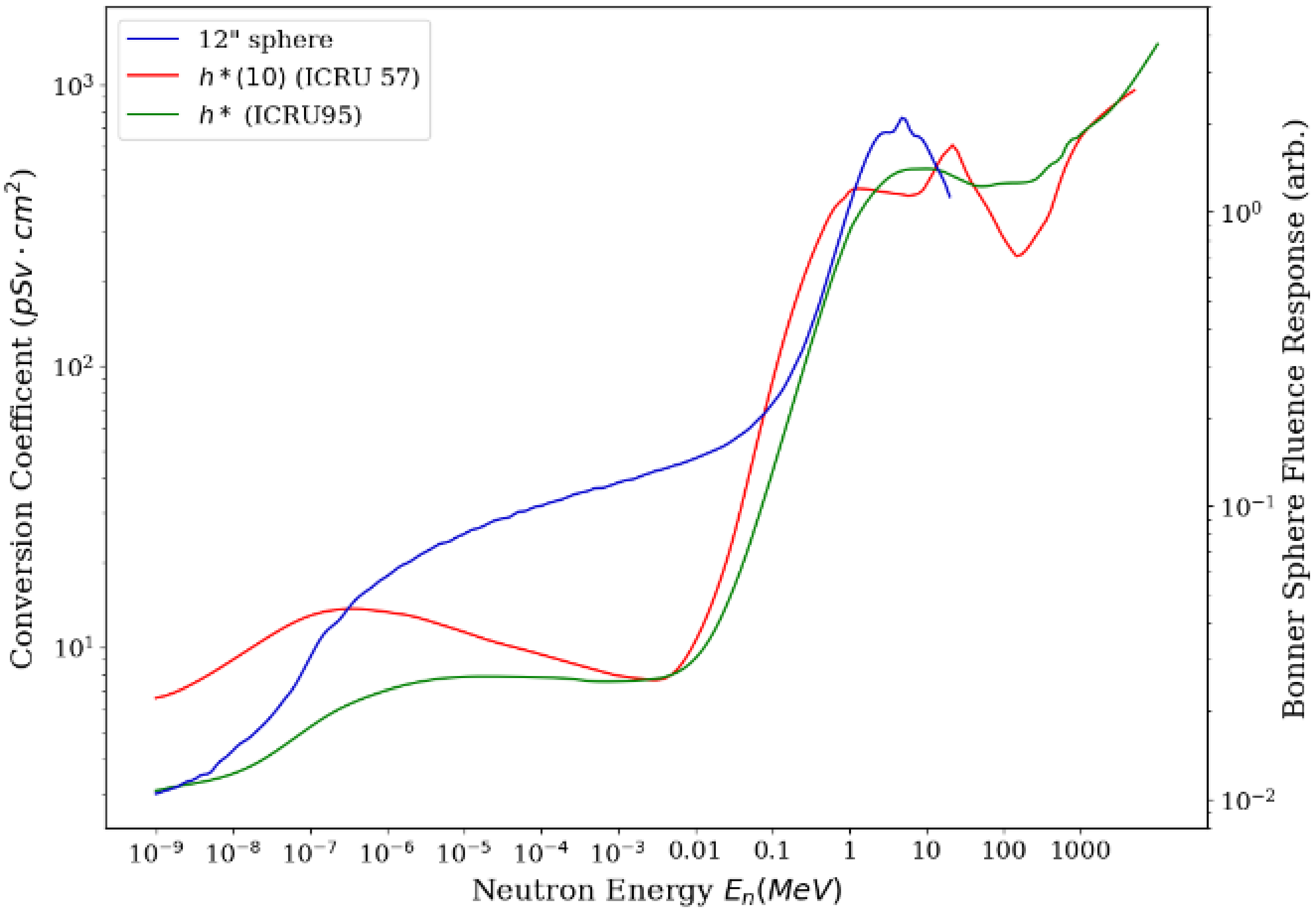
Evaluation proceeds similar to fixed-location spectrometer-detectors.

Adaptation of response matrix to *H** is required

Environmental Neutron Monitoring with TLD

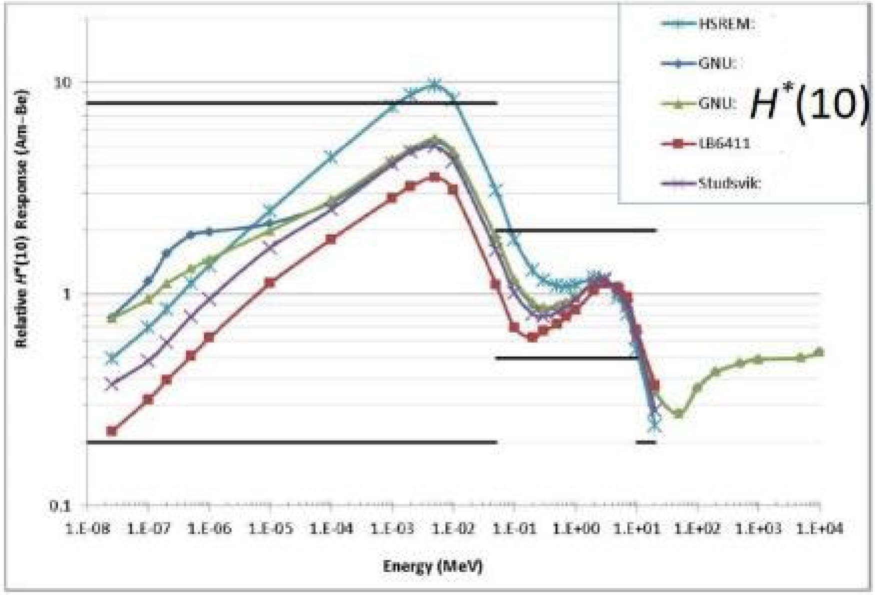


PE sphere,
central ^{6}LiF / ^{7}LiF
detector pair



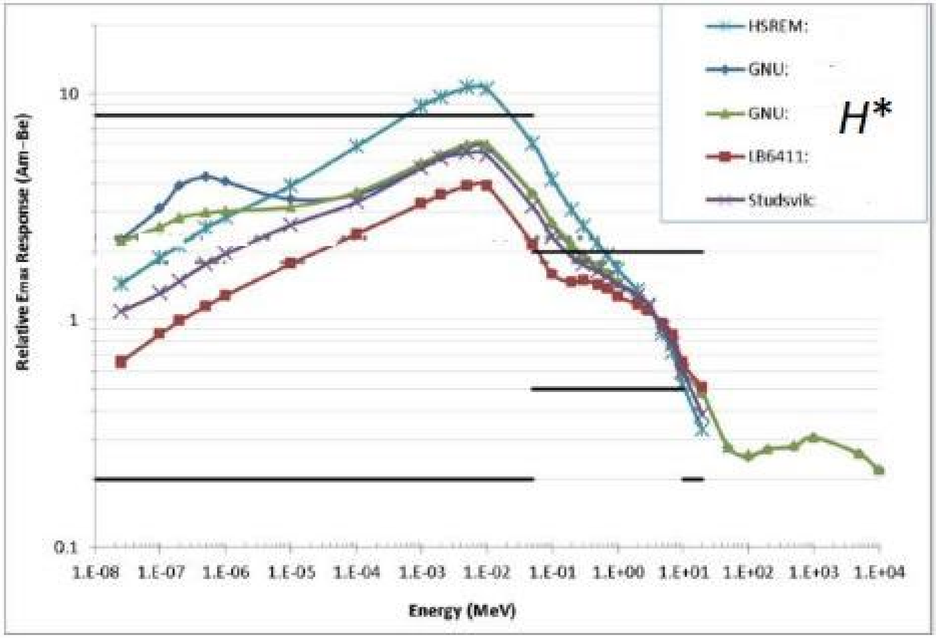
E. Piesch, B. Burgkhardt and others, 1980's

Response of Neutron Monitors (Rem-counters)



Black lines: IEC 61005 Ed. 3.0 b:2014 recommended response interval

Re-assessment of IEC acceptance regions required



As previously, standard Rem-counter response in mono-energetic fields within a large factor

No significant change for use at $E_{\text{kin}} < 20$ MeV

Field calibration may be necessary

J S Eakins *et al* 2018 *J. Radiol. Prot.* **38** 688

Summary

- Photon ambient dosimeters with cut-off E > 50 keV nearly unaffected
  - Recalibration of sensitivity
- Ambient dosimeters for low photon energies:
  - Redesign of filter required (or algorithm for multi-detector types)
- Spectrometer-based ambient dosimeter (Scintillators or HpGe for photons, Bonner spheres for neutrons)
  - Re-evaluate the response matrix for H^*
- Neutron rem-counters continue to give “good estimate”
  - Recalibration, adaptation of acceptance limits by IEC

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